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THE EFFECT OF SURFACES ON
THE MECHANICAL BEHAVIOR OF METALS

TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-63-101

March 1963

Directorate of Materials and Processes
Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

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Project 7353, Task 735303
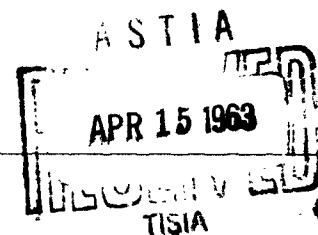
(Prepared under Contract No. AF33(616)-7976
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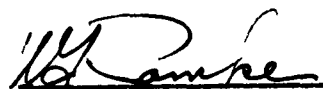I. R. Kramer, author)

FOREWORD

This report was prepared by the Martin Company under USAF Contract No. AF33(616)-7976. This contract was initiated under Project No. 7353, "Characterization of Solid Phase and Interphase Phenomena in Crystalline Substances," Task No. 73503, "Surface Condition and Mechanical Response." The work was administered under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, with Dr. B. K. Morse acting as project engineer.

This report covers work from 1 January to 31 December 1962.

ABSTRACT

The activation energies for plastic flow of aluminum, copper and gold were found to decrease as functions of the rate of metal removal. The decrease in activation energy was largest for aluminum and smallest for gold. As calculated by the usual methods, the activated volume for aluminum decreases with the polishing rate; however, it is shown that this method of determining the activated volume is incorrect. A study of the metal recovery process showed that it is associated with the ability of dislocations to escape from the crystal and the relaxation of dislocations in the debris layer. The activation energy at low strains for aluminum crystals is related almost entirely to the debris layer.

This Technical Documentary Report has been reviewed and is approved.

W. G. RAMKE
Actg. Chief, Advanced Metallurgical
Studies Branch
Metals and Ceramics Laboratory
Directorate of Materials and Processes

CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

That the surface plays an important role in plastic deformation processes has been adequately demonstrated[1,2,3,4]. Of particular interest at this time are the observations[4] that the creep rate of single crystals of face-centered cubic metals was increased markedly when specimens were polished during the deformation process. It was also noted that whenever the current density of the electrolytic polishing bath was changed from a low value to a high value, the creep rate of gold specimens increased gradually with time, and only after several minutes had elapsed was the steady-state value reached. These observations were interpreted in terms of a dislocation debris layer at the surface regions of the crystal This layer, which appears to be a region containing a high concentration of dislocations, not only will impede the egress of dislocations, but will also provide a barrier against which dislocations may pile up. By this means, a stress which opposes the motion of dislocation will be generated. It is considered that this stress must be taken into account in any theory which describes the plastic deformation process. Accordingly, the net stress, τ, acting on a dislocation may be written as

$$\tau = \tau_a - \tau_i - \tau_s \qquad (1)$$

where τ_a is the applied shear stress, τ_i is the stress due to internal obstacles, and τ_s is the stress resulting from the debris layer. It should be noted that if dislocations pile up against the debris layer, τ_s will be a long-range stress, whereas the distance over which τ_i acts is small.

For deformation which occurs by an intersection mechanism[5,6]

$$\dot{\gamma} = A e^{-\frac{U}{kT}} \qquad (2)$$

and

$$U = U_0 - V\tau \qquad (3)$$

where U is the activation energy for plastic flow, $\dot{\gamma}$ the shear strain rate, U_0 the energy necessary to form a jog and an associated constriction, V the activated volume, T the temperature (°K), and τ the stress acting on the dislocation.

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From Eq. (1) and (3)

$$U = U_0 - V (\tau_a - \tau_i - \tau_s) \tag{4}$$

and it is seen that if τ_s decreases, the activation energy, U, must decrease if V remains constant. However, as will be shown, V is a function of the surface conditions.

It follows further that, if the presence of a debris layer can affect the activation energy, other mechanical properties, such as the yield stress after prior plastic deformation, may be influenced by its removal.

In their work on aluminum, Dorn and coworkers[7] reported that at low strains the activation energy was 3400 cal/mole and at high strains it was 28,000 cal/mole. The lower value was interpreted in terms of the energy necessary to overcome the Peierls force, while the higher value was associated with the energy necessary for dislocations to move by a cross-slip process. It will be shown that the lower activation energy is associated with the surface debris layer.

II. EXPERIMENTAL PROCEDURE

Single crystals having a nominal cross section of 1/8 of an inch were prepared by a modified Bridgman technique using a multiple-cavity graphite mold. The initial purity of the metals was 99.997%, 99.999%, and 99.999% for aluminum, copper and gold, respectively. The orientation of the specimens is given in Fig. 1.

The measurement of the activation energy as a function of the rate at which the metal was removed was conducted in the same apparatus as described previously[4]; however, to minimize problems associated with thermal expansion, the support arms of the system were made of a low expansion alloy. The effect was measured by two methods. In one method, the activation energy was determined by the method suggested by Dorn and coworkers[7]. The creep tests were conducted near room temperature until a given strain was reached, and then the temperature was changed about 5°C and the new creep rate determined. Because of the very small value of the activation energy at low strains, thermal gradients and small variations in temperature, imposed when the temperature of the system was changed, induced relatively large errors. It was determined that when part of the load was removed during the creep test to reduce the creep rate to zero, the creep rate upon reloading was the same as it was previously, and no recovery occurred during the time required to change the temperature of the specimen. Accordingly, a procedure was adopted wherein the specimen was allowed to creep at a temperature T_1 until a given strain was reached. Ten percent of the load was removed and the current through the electrolytic cell shut off. A bath maintained at a temperature T_2 was then placed around the specimen and the temperature of the system was allowed to come to thermal equilibrium. The current was then turned on, and after a very short delay to establish that no creep was taking place, the load was brought up to its original value.

The activation energy was calculated from the equations

$$\dot{\gamma} = A e^{-\frac{U}{kT}} \tag{5}$$

$$U = \frac{k (\ln \dot{\gamma}_1 - \ln \dot{\gamma}_2)}{\frac{1}{T_2} - \frac{1}{T_1}} \tag{6}$$

3

where

A   = frequency factor

$\dot{\gamma}_1$ and $\dot{\gamma}_2$ = shear strain rates at the same strain and at temperatures T_1 and T_2 °K.

k   = Boltzmann constant

U   = apparent activation energy.

In the other method, the change in U was determined by measuring the change in strain rate, $\dot{\gamma}$, when the current density was changed suddenly. The change in activation energy, ΔU, was obtained from the equation

$$\frac{\dot{\gamma}_a}{\dot{\gamma}_b} = e^{-\frac{\Delta U}{kT}} \tag{7}$$

$$-\Delta U = kT \ln \frac{\dot{\gamma}_a}{\dot{\gamma}_b} \tag{8}$$

where the subscripts refer to the rate of metal removal. For these experiments, this method of determining ΔU is more accurate than that of taking the difference of the U values obtained by the change in creep rate with instantaneous changes in temperature (Eq. (6)). The errors introduced by inaccuracies in the temperature measurements are small. From Eq. (8),

$$\frac{d(\Delta U)}{dT} = -k \ln \frac{\dot{\gamma}_a}{\dot{\gamma}_b} \tag{9}$$

and experimentally, it was found that if the current density change was 0.5 amp/in.^{2}, the value of $\ln \dot{\gamma}_a / \dot{\gamma}_b$ was never greater than 2.4. Thus, even with a temperature error of 10° C, the d(ΔU) is 48 cal/mole, or about 2%.

In determining the change of U as a function of the rate of removal, the current density of the cell was changed in increments of 0.5 amp/in.^{2}

up to a value of 2 amp/in.^{2}. Preliminary experiments were conducted to determine whether ΔU values obtained in this manner were additive. For these measurements, a series of determinations were made wherein the current density changes of 1 amp/in.^{2} as well as a mixed series of 0.5 amp/in.^{2} and 1 amp/in.^{2} were used. From these measurements, it was found that the ΔU values as a function of polishing rate was the same regardless of the size of the current density change. For the ΔU determinations of copper and gold, the strain rate measurements were usually made when the current density was changed from a high value to a low value. The ΔU values obtained in this way agreed with those obtained when the current density changes were made in the opposite sense if the strain rates were measured just after the slow creep rate period ended.

Because of the necessity to measure the small changes in strain rate associated with the low activation energy of aluminum, the sensitivity of the electronic components was such that it was possible to measure strains of 6×10^{-6}. With this sensitivity, no drift was detected over an eight-hour period. To maintain a constant current through the electrolytic polishing cell, an automatic current regulator was used. A methyl alcohol-nitric solution was used as the polishing bath for aluminum, a phosphoric acid bath for copper, and aqua regia for gold.

For the specimens used in the tensile studies, a 200-pound Instron tensile machine was used. This tensile machine was equipped with an automatic recorder with which it was possible to measure deformations to within 3×10^{-5} inch and loads to within 0.01 pound.

In all cases, the shear stress values have been corrected to account for the change in cross-sectional area due to the removal of metal by electrolytic polishing during the test[1].

III. EXPERIMENTAL RESULTS

The effect of surface removal on the apparent activation energy, U, of aluminum single crystals is shown in Fig. 2. For specimens which were not polished during the creep tests, the average activation energy value was 4800 cal/mole when the shear strain, γ, did not exceed 4% and 22,500 cal/mole when γ was greater than 7.5%. These will be referred to as Region A and Region B, respectively. Lytton, et al.[7] obtained values of 3400 cal/mole at strains less than 13% and 28,000 cal/mole at strains greater than 25%. The difference in the inflection point is probably due to the difference in the orientation of the specimens used in the two investigations; however, we can offer no explanation at the present time for the lack of agreement of the activation energy value in Region A.

In Fig. 3 are the changes in the apparent activation energy, U, as a function of strain when the specimens were polished at various rates. These values have been incorporated in Fig. 2 as the solid lines without the data points. For the various polishing rates used in these experiments, the ΔU for a constant polishing rate was found to be independent of strain. However, the activation energy decreased continuously as the rate of removal of the metal was increased. For specimens deformed within Region A (Fig. 4), the activation energy was 4800 cal/mole when R was zero and 1480 cal/mole when R was 50×10^{-5} in./min. Also seen in Fig. 4 is the agreement of the values of U as a function of the rate of metal removal when the measurements were made by changing the temperature of the specimen as compared to those obtained by changing the current density of the polishing bath. The activation energies for the latter case were obtained by subtracting the appropriate ΔU values given in Fig. 3 from the activation energy obtained without removing metal during the deformation process.

The activation energy of high purity polycrystalline aluminum also changed as a function of the rate of metal removal (Fig. 5). Within the experimental error, the ΔU at a given polishing rate is the same for the polycrystalline specimens as it is for the single crystals.

The activation energy of gold and copper is also influenced by the surface barriers. As shown in Table 1, the activation energy as determined by the method associated with Eq. (6) for gold and copper is 21,960 $\pm$2760 and 27,600 $\pm$3850, respectively. Landon et al.[8] reported a value of 27,800 cal/mole for copper. The activation energy for gold is reported[9] to be 30,000 $\pm$11,000 cal/mole. The activation energy for polycrystalline aluminum was determined to be 33,000 $\pm$2000 cal/mole which compares favorably with 34,500 cal/mole reported elsewhere.[7] Unlike single

crystals of aluminum, the activation energy for gold and copper remains constant as a function of strain (Table 1 and Fig. 6). In addition to showing the constancy of ΔU with strain, Fig. 6 contains data points at $R = 25 \times 10^{-5}$ in./min which were obtained by changing the polishing rate directly from $R = 0$ to $R = 25 \times 10^{-5}$ as well as data obtained by the addition of the incremental value of ΔU which resulted from the change of $R = 0$ to $R = 12.5 \times 10^{-5}$ in./min and $R = 12.5 \times 10^{-5}$ in./min to $R = 25 \times 10^{-5}$ in./min.

The change in activation energy as a function of the rate of metal removal for aluminum, copper and gold is given in Fig. 7. It is seen that the effect of surface removal is largest for aluminum and smallest for gold.

In Fig. 8 the effect of removing the surface layers at various rates is reported in terms of $\beta = V/kT$, where V is the activated volume. These data were obtained by the usual method of changing the strain rate during tensile deformation. In these tests, the strain rate, $\dot{\epsilon}$, was changed between 10^{-4} sec^{-1} and 10^{-5} sec^{-1} and the value for β was calculated from the equation

$$\beta = \frac{V}{kT} = \frac{\Delta \ln \dot{\gamma}}{\Delta \tau_a} \tag{10}$$

where $\Delta \tau_a$ is the change in the applied shear stress which occurred when the strain rate was changed suddenly. Equation (10) may be derived directly from Eqs. (3) and (5) by assuming $\tau = \tau_a$.

When Eq. (10) is used to calculate the activated volume, it is found that an increase in the rate of metal removal causes β to decrease. Of interest is the effect of the activated volume when the time of straining at the lower strain rate was increased. In Fig. 9, Curve A was derived from a test in which the metal was removed at a rate of 12.5×10^{-5} in./min and the specimen was deformed for one minute at a strain rate of 10^{-5} sec^{-1} before the strain rate was changed to 10^{-4} sec^{-1}. The time of straining at the higher rate was 0.1 minute. In Curve B, the test conditions were the same except that the specimens were allowed to deform for 5 minutes at $\dot{\epsilon} = 10^{-5}$ before changing to the higher strain rate. The time expended at the higher strain rate was 0.25 minute. As a result of this modification in the test procedure, the activated volumes given in curve A and curve B differed considerably.

During the course of investigating the creep behavior, it was found that when a sufficient amount of the load was removed during test to reduce the creep rate to zero, the creep resumed if the specimen was polished continuously. The data presented in Fig. 10 shows the relationship at various polishing rates between the decrease in the applied stress on an aluminum single crystal and the time, t_d, for the creep to start. The straight line drawn through the points was derived by the method of least squares. It is seen that t_d is directly proportional to the decrease in the applied stress and the rate at which the metal is removed. The time, t_d, is thus directly related to ΔX, the amount of metal removed.

To determine whether the resumption of creep was due to the change in stress associated with the decrease in the cross-sectional area of the specimen, a test was conducted, without polishing, wherein the shear stress was reduced by 25 psi during the creep process. Small weights of 5 grams were added in increments until the creep started again. Initially, the stress, τ, on the specimen was 900 psi and after the removal of 25 psi, it was necessary to add sufficient weight to bring the stress back to 885 psi before creep started again. To account for the resumption of creep in terms of the change in cross-sectional area, it would require a removal of 0.001 inch from the cross section to increase the stress to 885 psi after the stress was reduced to 875 psi. This would require 2, 4 and 8 minutes at a polishing rate used in curves 1, 2 and 3, respectively, in Fig. 10. However, as may be seen, the time for creep to start again for this reduction in stress was 0.25, 0.5 and 1 minute for the three cases (curves 1, 2, 3). During this time, the amount of metal removed was 1.25×10^{-4} inch, which is too small to account entirely for the increase in stress necessary to start the creep process.

The removal of the metal from the surface of the specimen not only affects the delay time for creep, but also the initial yield stress after the load has been removed. When a single crystal of aluminum was strained to about 15% and the stress removed, upon reloading, after a rest of 13 minutes at nearly zero load, a yield point appeared (Fig. 11). However, upon reloading until a strain of 15.8% was reached and then removing 0.006 inch from the cross section, the initial yield stress was lowered and the yield point was eliminated. When the unloading-reloading cycle was repeated at higher strains, the yield point reappeared and no recovery occurred even though the specimen was allowed to rest for 25 minutes before reloading. The decrease in the yield stress, $\Delta\tau$, as a function of the amount of metal removed, is shown in Fig. 12. The $\Delta\tau$ values have been corrected to take into account the change in the cross-sectional area of the specimen.

9

IV. DISCUSSION

The experimental observation, that the apparent activation energy is decreased as the rate of metal removal is increased during plastic deformation, shows that at low temperatures the activation energy is strongly influenced by the surface barriers. For aluminum, at low strains, the activation energy appears to be determined almost entirely by the rate of escape of the dislocations through the debris layer. It does not seem likely that the Peierls force can account for the values of the activation energy at low strains. This force should be independent of the surface effects.

At the higher strains, the rate of escape of dislocations still plays an important role; however, internal barriers are more important. It appears that in addition to the strength of the internal barriers there is a back stress emanating from the surface. This may be visualized as a stress due to a piled-up array of dislocations against the debris layer in the surface regions of the specimen. From this point of view, the net stress acting on a dislocation must be $\bar{\tau}_a - (\bar{\tau}_i + \bar{\tau}_s)$.

If it is assumed that for copper, gold and aluminum at the high strains, the deformation process is controlled by an intersection mechanism, Eq. (3), which describes this process, must be modified to take into account the τ_s term in accordance with Eq. (4).

From the experimental results showing that the activation energy decreases with the rate of metal removal, it can be shown that the activated volume must increase.

According to Eq. (4) and $\Delta U = U_1 - U_2$, where the subscripts refer to the two polishing rates R_1 and R_2, and $R_1 > R_2$

$$\Delta U = V_2 (\tau_{a1} - \tau_{s1} - \tau_{i1}) - V_1 (\tau_{a2} - \tau_{s2} - \tau_{i2}) \tag{11}$$

When the activation energy is determined, the strain rates before and after the change in temperature or polishing rate are measured at the same strain and stress. Therefore, it is reasonable to assume that $\tau_{s1} = \tau_{s2}$; $\tau_{i1} = \tau_{i2}$; and $\tau_{a1} = \tau_{a2}$. Therefore,

$$\Delta U = (\tau_a - \tau_i) (V_2 - V_1) - \tau_s (V_2 - V_1) \tag{12}$$

11

For plastic flow to occur

$$\tau_a > \tau_i + \tau_s > 0 \qquad (13)$$

and

$$\tau_a - \tau_i > \tau_s \qquad (14)$$

Experimentally, $\Delta U < 0$ when $R_1 > R_2$ $\qquad (15)$

Therefore, $V_1 > V_2$ and $\beta_1 > \beta_2$ $\qquad (16)$

However, an analysis of the experimental data by Eq. (10) leads to $\beta_1 < \beta_2$.

The discrepancy between the values of the activated volumes calculated through the use of Eq. (10) and that predicted by Eq. (11) is due to the tacit assumption that $\Delta \tau_a$ is equal to $\Delta \tau$ where τ is the net force acting on the dislocation. Actually,

$$\beta = \frac{V}{kT} = \frac{\Delta \ln \dot{\gamma}}{\Delta \tau} = \frac{\Delta \ln \dot{\gamma}}{\Delta \tau_a - (\tau_i + \tau_s)} \qquad (17)$$

When a rapid change in strain rate is made, it may be reasonable to assume that $\Delta \tau_i$ is zero. However, this is not true for $\Delta \tau_s$. Previous experimental data[1] have shown that changes of the slope of Stages I, II and III with polishing rate are functions of the strain rate. Therefore, it follows that the rate of accumulation of dislocations in the surface regions, and hence τ_s, increases with the strain rate. Accordingly,

$$\frac{V}{kT} = \beta = \frac{\Delta \ln \dot{\gamma}}{\Delta \tau_a - (\tau_{s2} - \tau_{s1})} \qquad (18)$$

$$\beta_2 - \beta_1 = \Delta \beta = \frac{\Delta \ln \dot{\gamma}}{\Delta \tau_{a2} - (\tau'_{22} - \tau'_{12})}$$

$$- \frac{\Delta \ln \dot{\gamma}}{\Delta \tau_{a1} - (\tau'_{21} - \tau'_{11})} \qquad (19)$$

where $\tau_s \equiv \tau'$.

$\tau'_{ij} \equiv \tau_s$ at strain rate i and polishing rate j, β_1 and β_2 are for polishing rates R_1 and R_2 where $R_2 < R_1$.

To satisfy Eq. (16), $\beta_2 - \beta_1 < 0$

or

$$\Delta \tau_{a2} - (\tau'_{22} - \tau'_{12}) > \Delta \tau_{a1} - (\tau'_{21} - \tau'_{11}) \qquad (20)$$

It has been shown[4] that the change in slope of the various stages of face-centered cubic metals is a function of strain rate and the rate of metal removal. This relationship is shown schematically in Fig. 13. From this diagram it is seen that:

$$\Delta \tau_1 = \tau'_{21} - \tau'_{11} = \left(\frac{\partial \tau'}{\partial R}\right)_{\dot{\gamma}_2} \Delta R_1 - \left(\frac{\partial \tau'}{\partial R}\right)_{\dot{\gamma}_1} \Delta R_1 \qquad (21)$$

$$\Delta \tau_2 = \tau'_{22} - \tau'_{12} = \left(\frac{\partial \tau'}{\partial R}\right)_{\dot{\gamma}_2} \Delta R_2 - \left(\frac{\partial \tau'}{\partial R}\right)_{\dot{\gamma}_1} \Delta R_2 \qquad (22)$$

$$\Delta \tau_1 = \left[\left(\frac{\partial \tau'}{\partial R}\right)_{\dot{\gamma}_2} - \left(\frac{\partial \tau'}{\partial R}\right)_{\dot{\gamma}_1}\right] \Delta R_1 \qquad (23)$$

$$\Delta \tau_2 = \left[\left(\frac{\partial \tau'}{\partial R}\right)_{\dot{\gamma}_2} - \left(\frac{\partial \tau'}{\partial R}\right)_{\dot{\gamma}_1}\right] \Delta R_2 \qquad (24)$$

since $\Delta R_1 > \Delta R_2$ and the terms within the brackets are equal and positive:

$$\Delta \tau_1 > \Delta \tau_2 \qquad (25)$$

In the above derivation, it was assumed that in Fig. 13 the curves were linear. The inequality of Eq. (25) is still true if the curves are monotonic and the slopes at the larger strain rates are less negative than those at the smaller strain rates at the same polishing rate.

13

Experimentally, it has been shown that

$$\Delta \tau_{a1} < \Delta \tau_{a2} \tag{26}$$

Therefore, from Eqs. (25) and (26), the conditions of Eq. (20) are satisfied and it may be concluded that the activated volume should increase with faster rates of metal removal. To calculate the activated volume, Eq. (17) should be used; however, this is not possible at this time since the τ_s terms are not known.

In addition to its effect on the activation energy, the existence of a debris layer also influences the recovery process. The type of recovery which was found when the specimens were polished to decrease the debris layer has been designated as metarecovery[10]. The re covery process shown in Figs. 10 and 11 appears to be associated with a change in the dislocation concentration in the debris layer. It has been possible to show, from relaxation experiments, that after a specimen has been strained and then unloaded rapidly, dislocations can escape from the crystal if it is polished continuously after the stress is removed. The rate of relaxation was decreased markedly during the polishing period, showing that dislocations were moving out of the specimens as well as toward the interior. It is also possible that metarecovery and the delay time for creep are related. The delay time for creep and the recovery in the initial flow stress were found to be directly proportional to the amount of metal removed. This may be explained on the basis of the surface back stress, τ_s (Eq. (1)). A decrease in the τ_s terms would allow an increase in the net stress acting on the dislocations, and the initial yield stress upon reloading would be reduced. The delay time for creep is probably associated with two interdependent processes. One process is the rearrangement of dislocations in the debris layer as a function of time, and the other process is associated with the decrease in the dislocation concentration as the debris layer. The rearrangement process apparently occurs more easily when the dislocation concentration is reduced.

As shown in Fig. 7, the apparent activation energies of copper and gold are decreased when single crystal specimens are deformed while the surface layers are removed continuously. Although this decrease is consistent with the decrease in the stacking energy for the metals, other phenomena may play a role, for example, the nature of the oxide layer. Further studies will be necessary to interpret these observations properly.

14

It seems reasonable to explain the difference in curves A and B (Fig. 9) on the basis of the thickness of the debris layer. For a given rate of removal, the rate of accumulation of dislocations in the surface regions increases with the strain rate. Therefore, as the amount of strain at the high strain rate increases in comparison to that at the low strain rate, the number of dislocations in the surface debris layer will increase. At least in the cases when the measurements are made while surface removal is occurring, the value obtained for the activated volume will depend upon the amount of strain at the two strain rates.

V. CONCLUSIONS

The apparent activation energy, U, for aluminum, copper and gold single crystals and polycrystalline aluminum depends upon the rate of escape of dislocations. The change in activation energy with polishing rate for these metals appears to be related to the stacking fault energy; however, the effect of the oxide film may be important.

It has been shown that the calculation of the activated volume by the equation $V = kT \dfrac{\Delta \ln \dot{\gamma}}{\Delta \tau_a}$ is incorrect. To account for the change in activation energy as a function of the rate of removal, the stresses resulting from the debris layer must be taken into account according to Eq. (17).

The apparent activation energy for aluminum single crystals obtained at low strains is a measure of the amount of energy which must be expended to allow dislocations to escape from the crystal.

The delay time for creep and metarecovery are associated with the presence of the dislocation debris layer which exists in the region of the surface.

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TABLE 1

Activation Energy of Gold and Copper Single Crystals

Gold Au-119	Temperature 285° to 295° K	Copper Cu-109	Temperature 285° to 295° K
Apparent Activation Energy, u (cal/mole)	Shear Strain, γ (%)	Apparent Activation Energy, u (cal/mole)	Shear Strain, γ (%)
19,000	0.25	23,000	0.56
25,400	1.34	25,800	0.79
20,600	1.93	25,900	0.82
25,100	1.95	22,200	0.99
21,200	2.44	23,800	1.52
22,400	2.98	30,500	1.86
17,600	3.01	27,700	2.06
17,100	3.05	23,800	2.19
20,200	3.49	31,100	2.40
23,100	3.51	33,700	2.41
24,000	3.88	36,600	2.46
24,500	5.02	34,400	2.47
25,500	5.03	23,300	2.82
22,200	5.64	27,800	2.85
25,500	5.65	24,800	3.31
19,400	6.18	(27,600 ± 3850 a.d.) cal/mole	
18,500	6.34		
23,600	6.83		
23,700	6.98		
24,700	7.16		
19,000	7.28		
17,600	7.31		
16,300	7.48		
25,900	7.97		
26,800	7.98		
(21,960 ± 2759 a.d.) cal/mole			
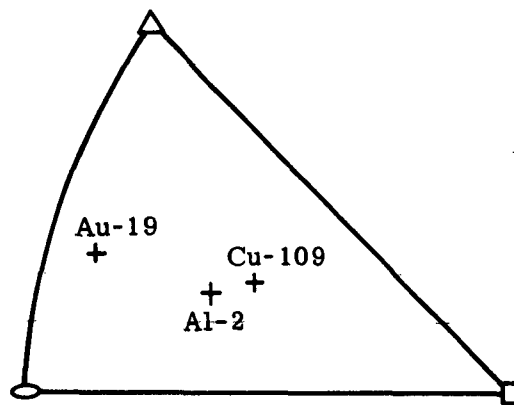
Fig. 1.   Orientation of Single Crystal Specimens
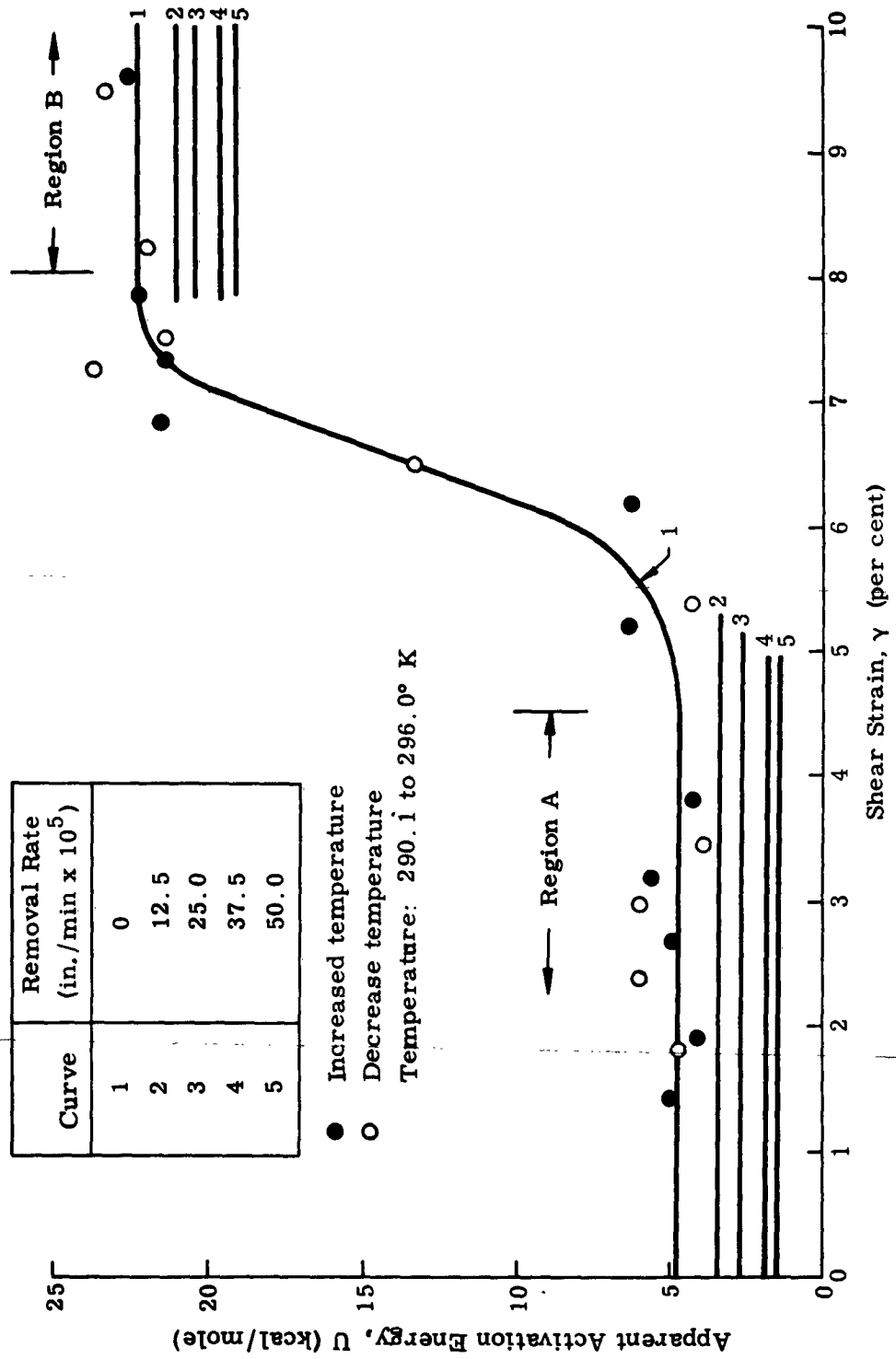
Fig. 2. The Apparent Activation Energy, U, for Aluminum Crystals as a Function of Shear Strain, γ, and Rate of Metal Removal

Curve	Removal Rate (in./min x 10^5)
1	0
2	12.5
3	25.0
4	37.5
5	50.0

● Increased temperature
○ Decrease temperature
Temperature: 290.1 to 296.0° K

Fig. 3. Change in Apparent Activation Energy, ΔU, for Aluminum Crystals with Rate of Metal Removal

23
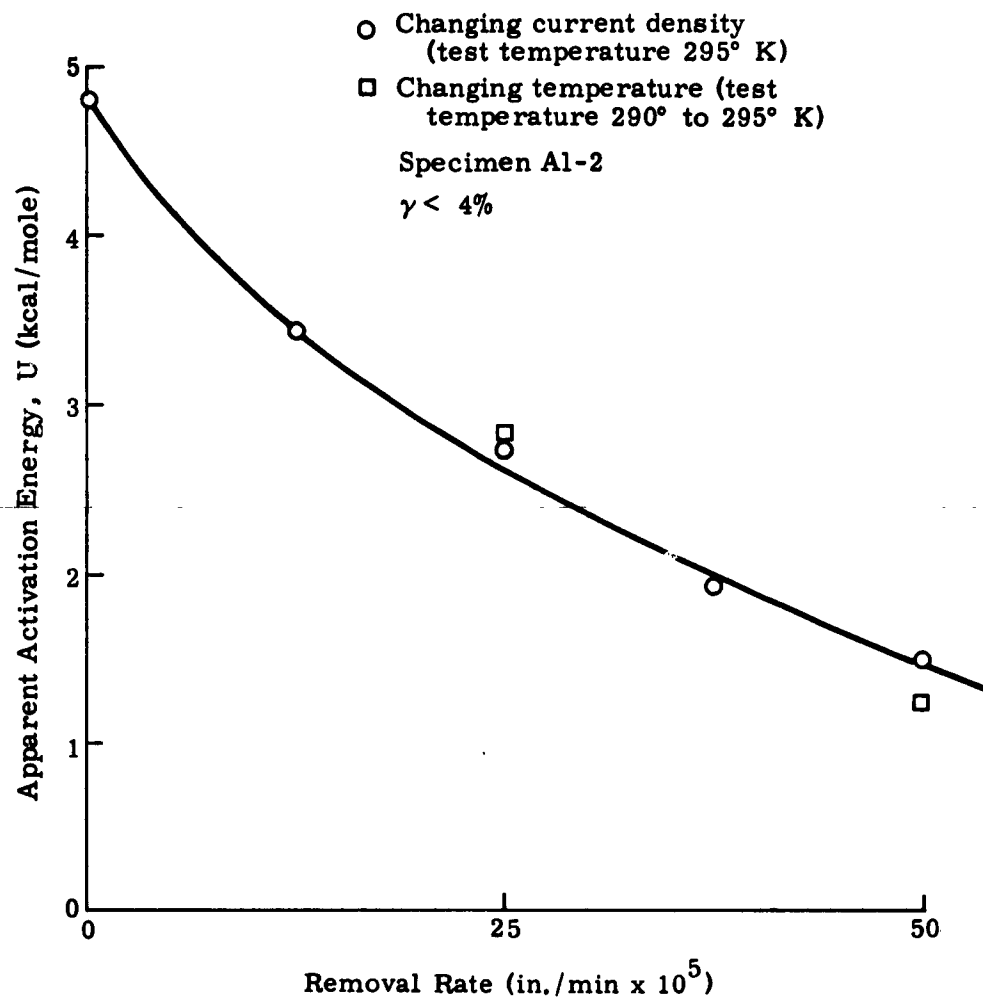
Fig. 4. Comparison of the Apparent Activation Energy for Aluminum Crystals as Measured by a Change in Temperature and a Change in Current Density ($\gamma < 4\%$)
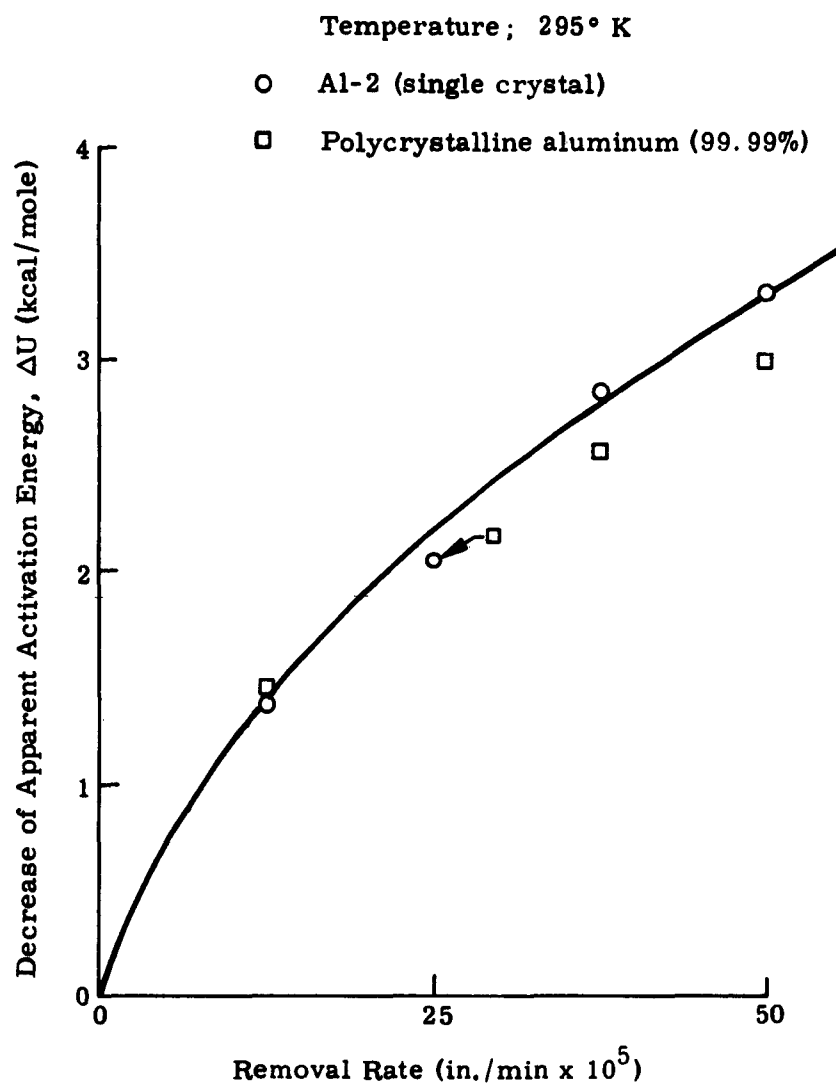
Fig. 5. The Change in the Apparent Activation Energy, ΔU, for Polycrystalline Aluminum with Rate of Metal Removal

Symbol	Removal Rate (in./min x 10^5)
○	0 ⟷ 12.5
□	12.5 ⟷ 25.0
■	0 ⟷ 25.0

Temperature: 295° K

Specimen Cu-109
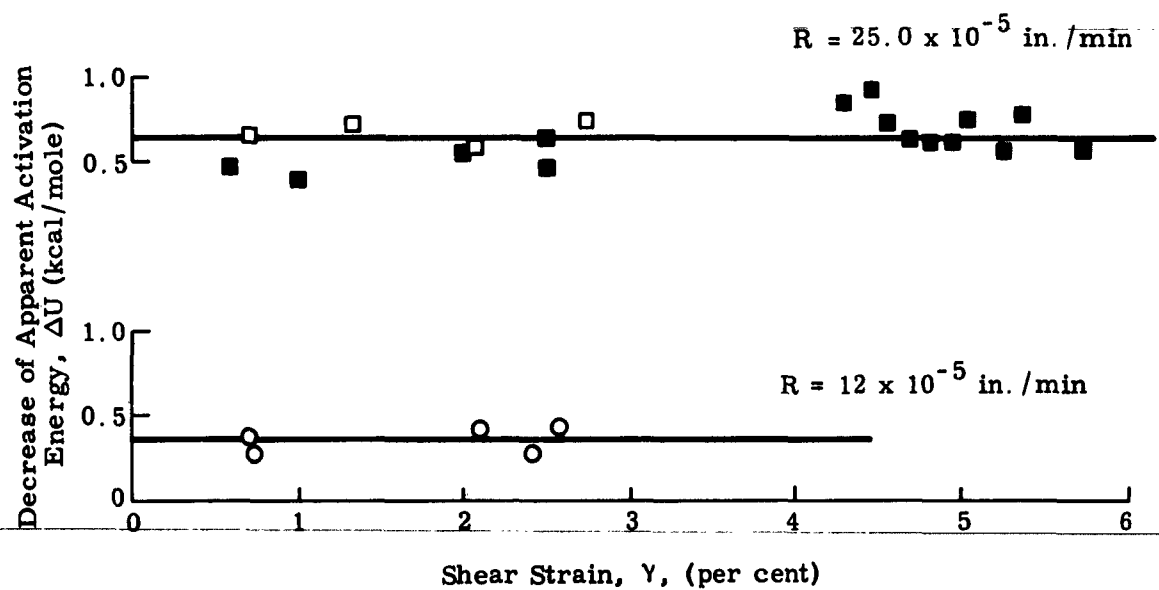
Fig. 6. The Change in the Apparent Activation Energy for Copper Crystals with Polishing Rate, R, and Shear Strain, γ
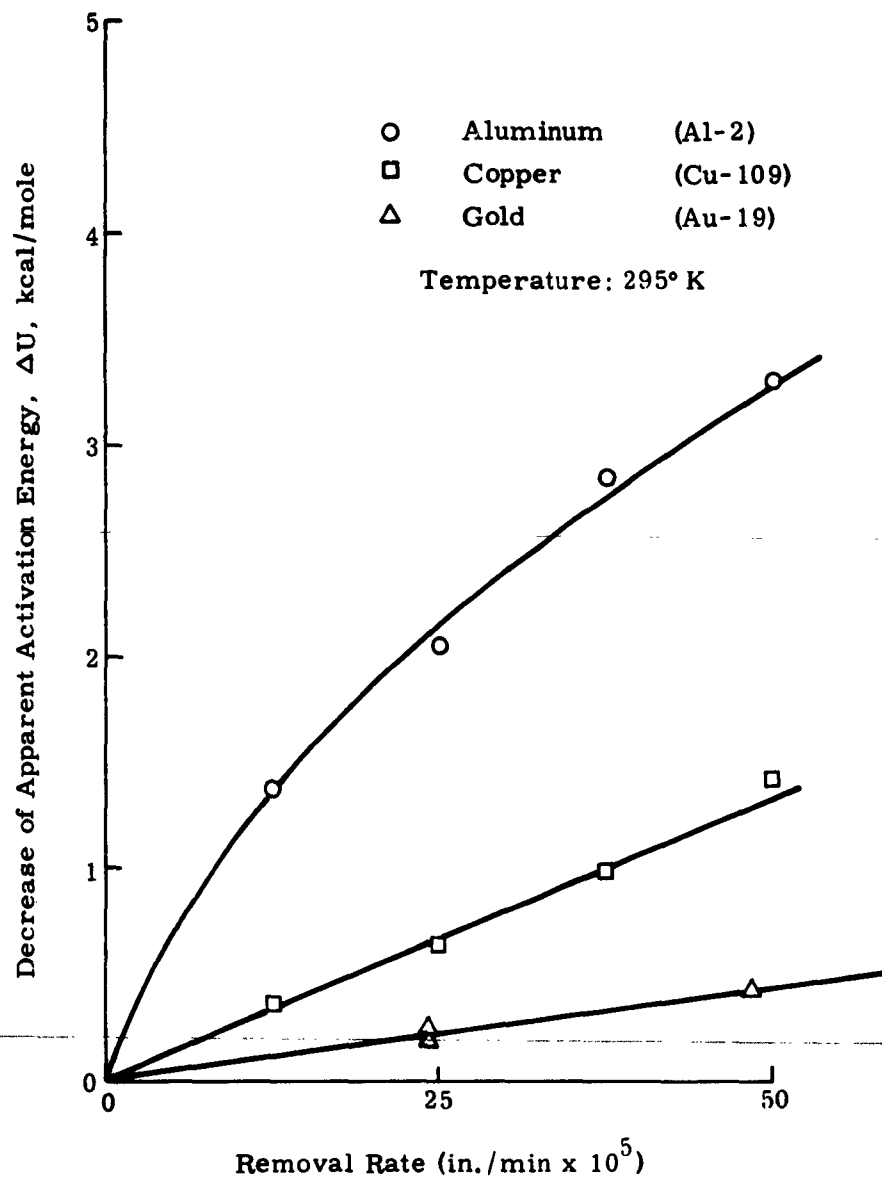
Fig. 7. The Change in the Apparent Activation Energy, ΔU, of Single Crystals of Aluminum, Copper and Gold as a Function of Rate of Removal, R
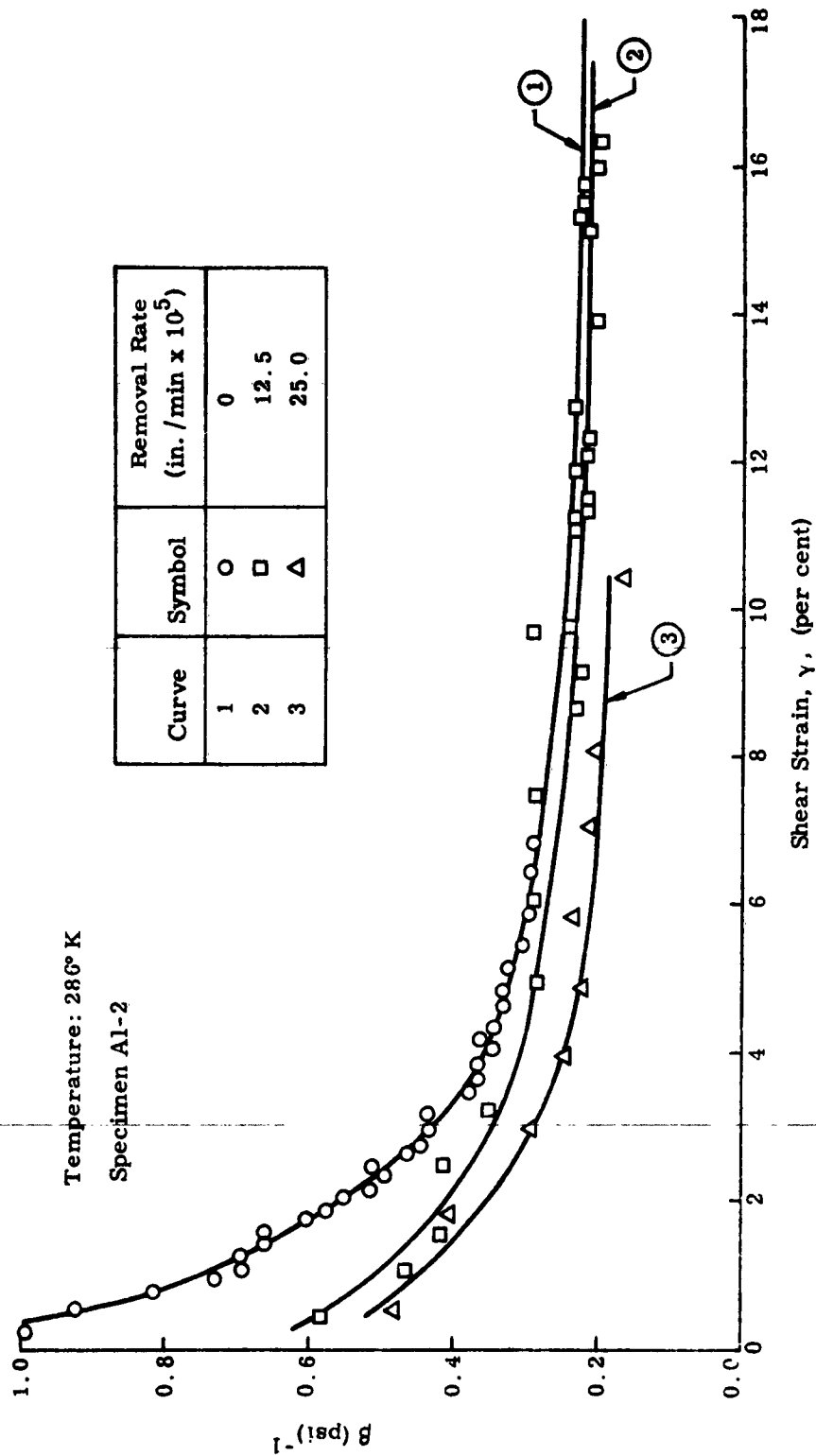
27

Temperature: 286° K

Specimen Al-2

Curve	Symbol	Removal Rate (in./min x 10^5)
1	O	0
2	□	12.5
3	△	25.0

β (psi)$^{-1}$

Shear Strain, γ, (per cent)

Fig. 8.   The Effect of the Rate of Metal Removal on the Activated Volume,
V = βkT for Aluminum Crystals

Curve-A--0.1 minutes at $\dot{\epsilon} = 10^{-4}$ sec^{-1}, 1 minute at $\dot{\epsilon} = 10^{-5}$ sec^{-1}

Curve-B--0.25 minutes at $\dot{\epsilon} = 10^{-4}$ sec^{-1}, 5 minutes at $\dot{\epsilon} = 10^{-5}$ sec^{-1}
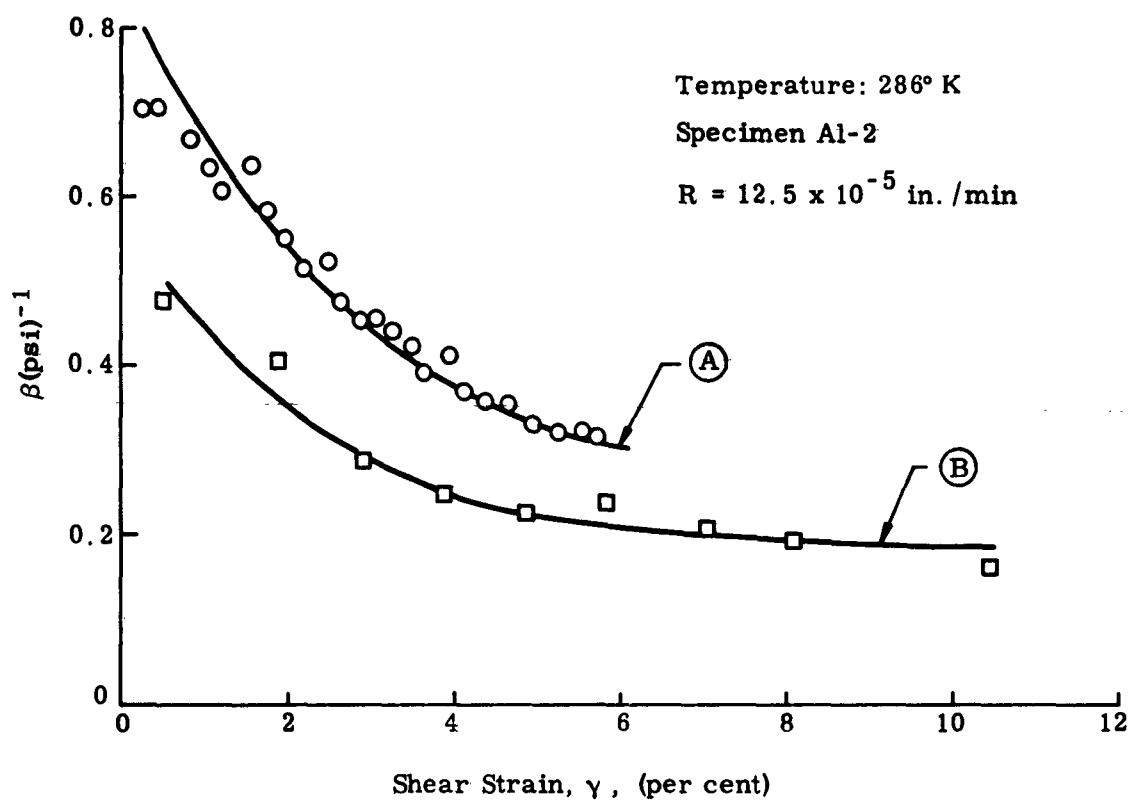
Fig. 9. The Effect of Time of Straining at $\dot{\epsilon} = 10^{-5}$ sec^{-1} and $\dot{\epsilon} = 10^{-4}$ sec^{1} on the Activated Volume

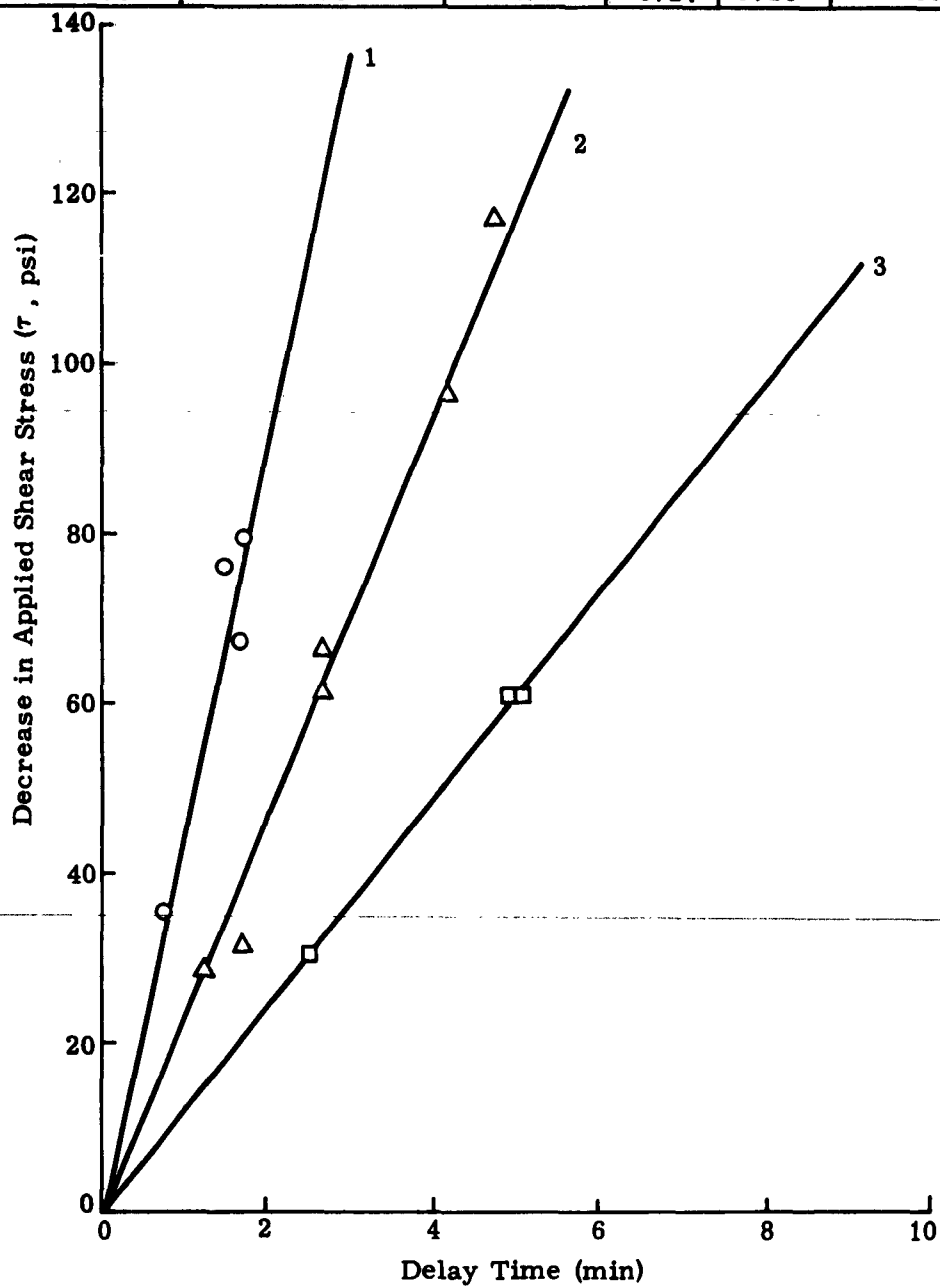| Curve	Temperature (°K)	Removal Rate, R (in./min x 10^5)	Slope, (psi/min)	Ratios		Initial Applied Shear Stress, (psi)
				$\frac{\phi_i}{\phi_1}$	$\frac{R_i}{R_1}$	
1	296.4	50	89.2	1.00	1.00	741
2	295.2	25	46.5	0.52	0.50	1272
3	290.8	12.5	24.3	0.27	0.25	1096

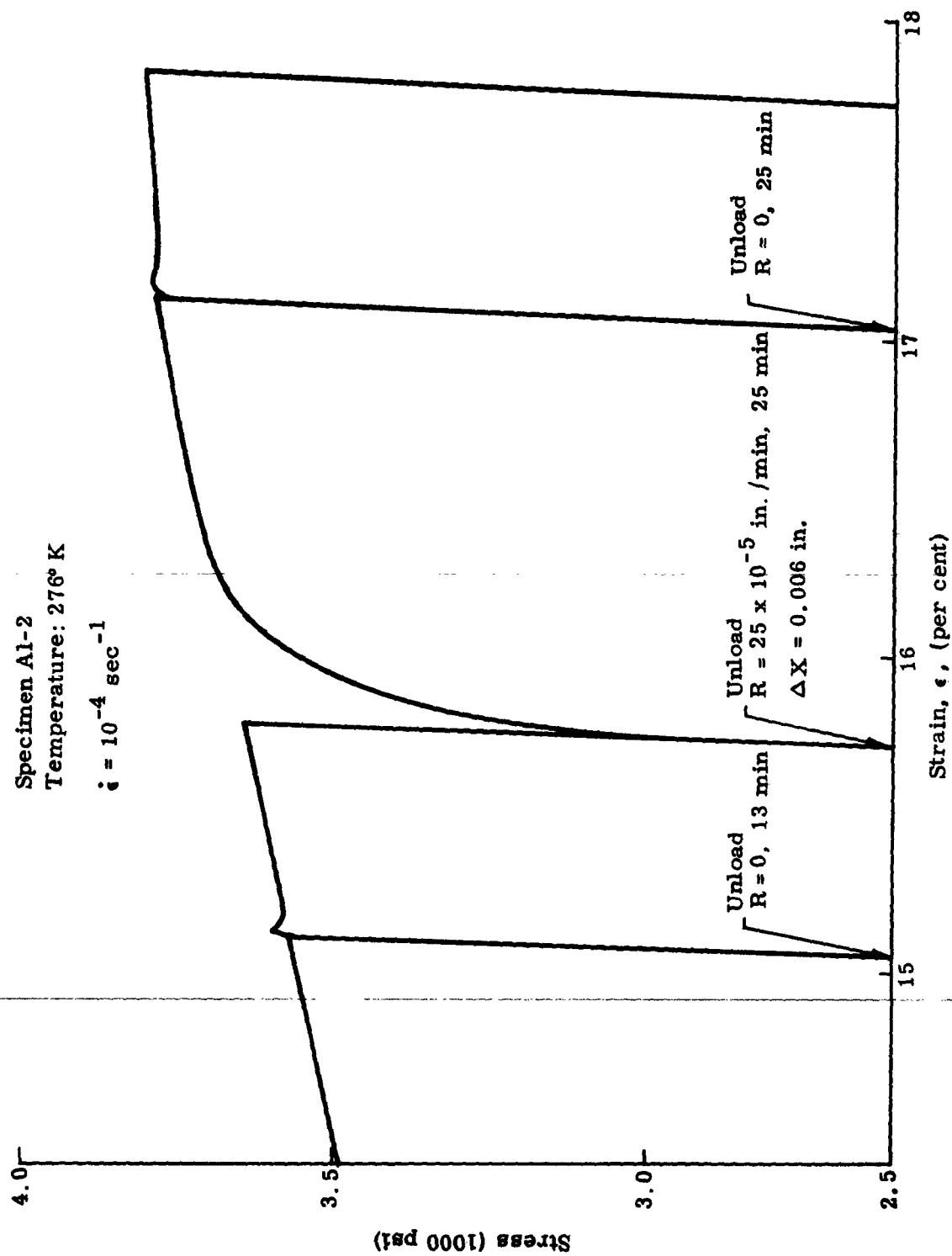Fig. 10. Effect of a Decrease in the Applied Stress on the Delay Time for the Resumption of Creep for Aluminum Crystals Al-2

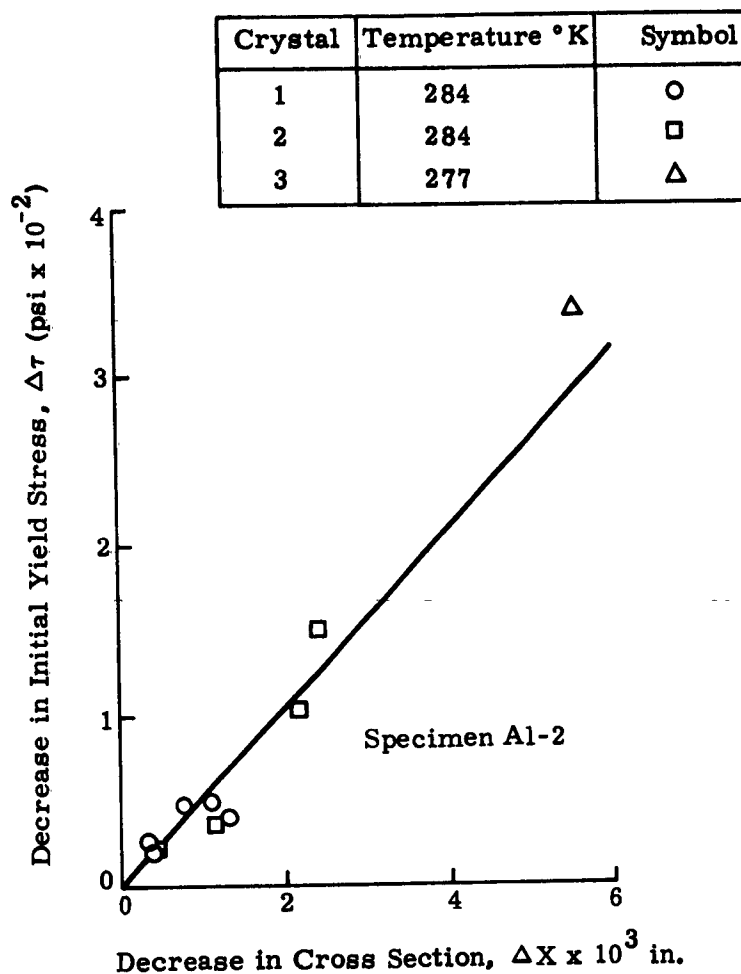Fig. 11. The Effect of Removing the Surface Layer on the Initial Yield Stress

Specimen Al-2
Temperature: 276° K

$\dot{\varepsilon} = 10^{-4} sec^{-1}$

Unload
R = 0, 13 min

Unload
R = 25 x 10^{-5} in./min, 25 min
ΔX = 0.006 in.

Unload
R = 0, 25 min

Stress (1000 psi)

Strain, ε, (per cent)

31

Crystal	Temperature °K	Symbol
1	284	O
2	284	□
3	277	△

Fig. 12. Relationship Between Decrease in Cross Section of Specimen and Decrease in Initial Yield Stress
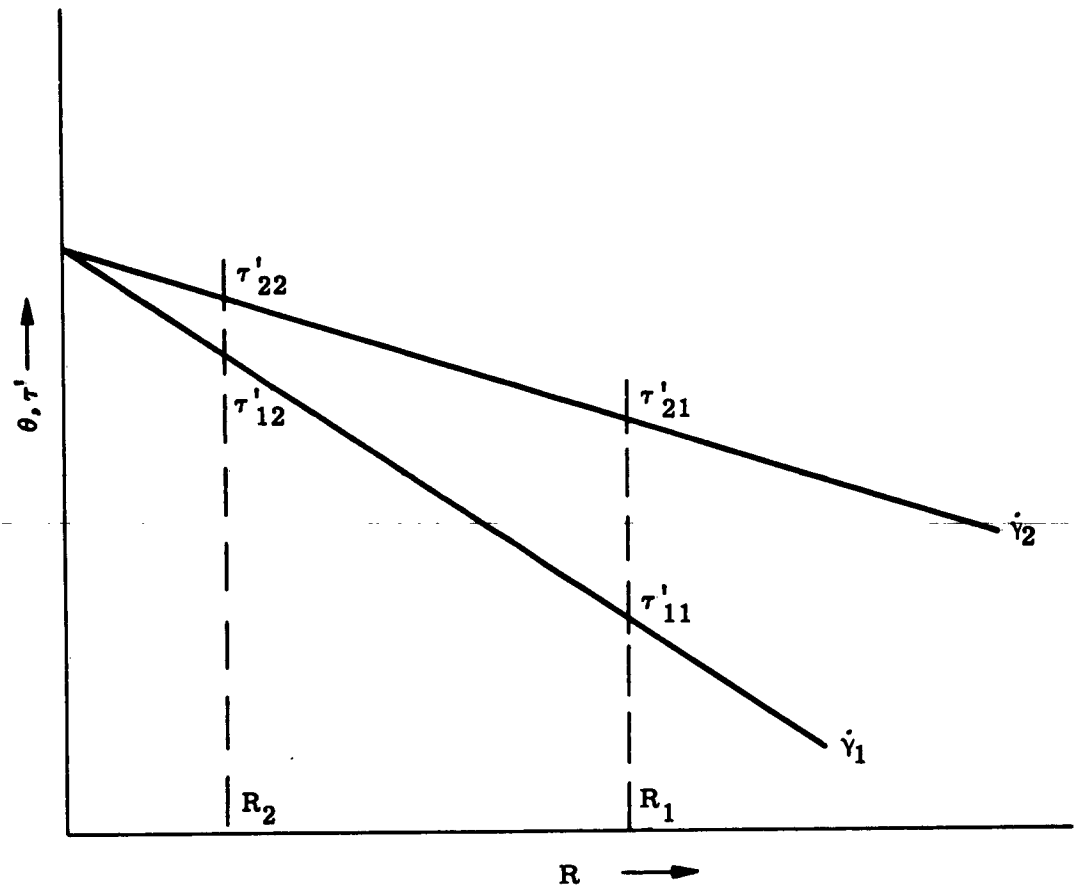
Fig. 13.   Schematic Relationship Between τ' and R

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